Initial studies of irradiated Ga doped LGADs

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on behalf of RD50 project collaborators:
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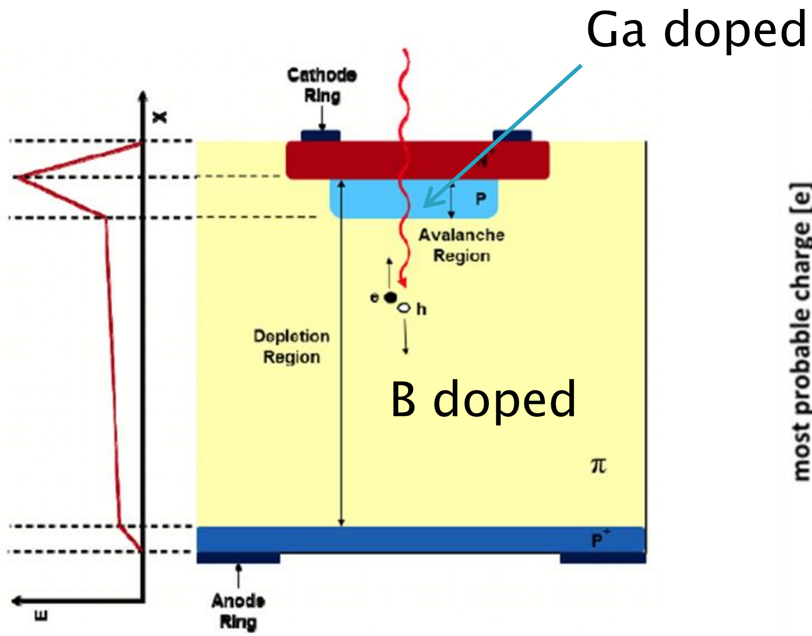
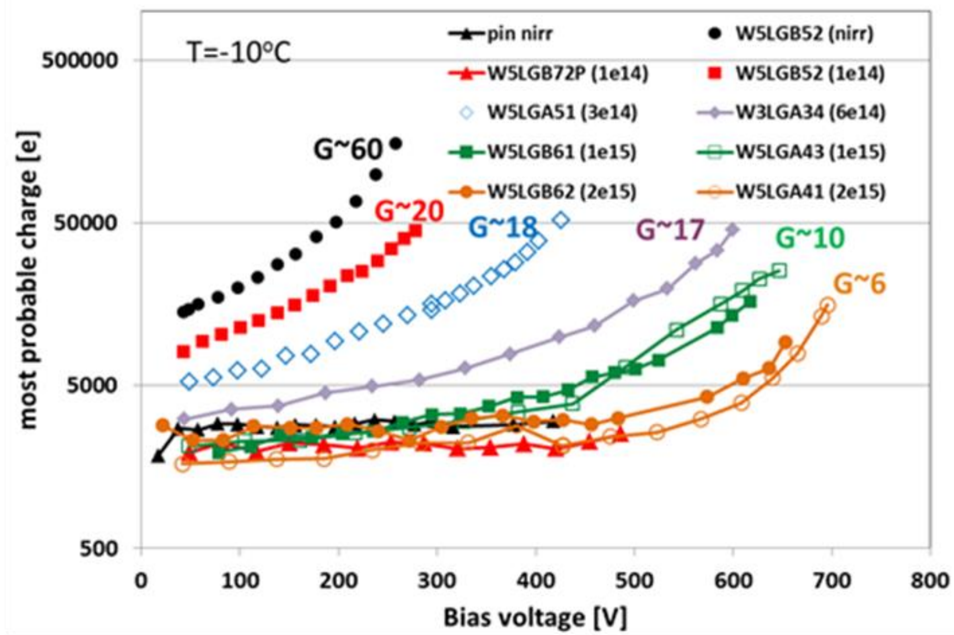
Motivation

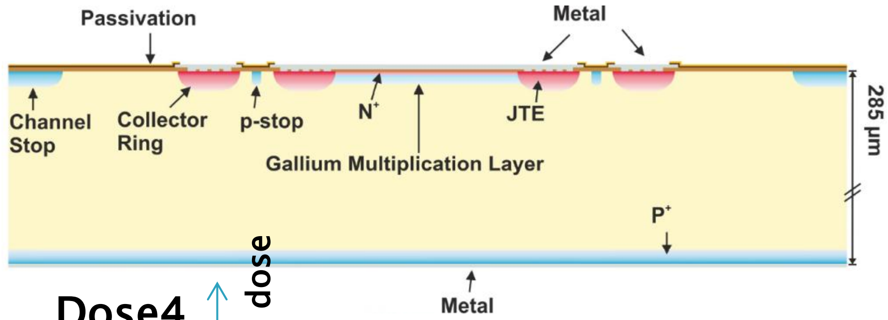




- Effective initial acceptor removal is the main cause of performance degradation of LGADs
- Different strategies are investigated to mitigate the removal (C-spray, prolonged annealing). Replacement of B with Ga (see Santander talk) was one of them.
- CNM produced first LGADs where boron was replaced by Ga -> main goal is to determined their radiation hardness
- It is crucial for HL-LHC operations to provide radiation hard LGADs for precise timing measurements

Ga-LGAD – samples

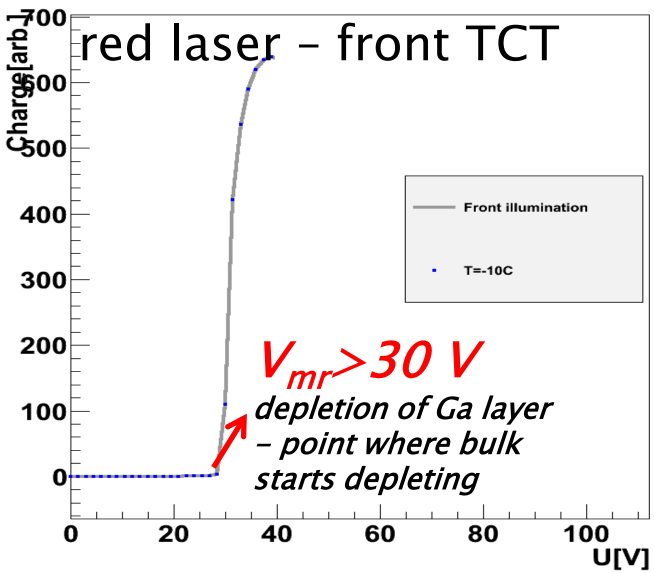
- 4 different dose splits (Dose1, Dose2, Dose3, Dose4) and control devices without Ga implant
- Before irradiation the devices break down after depletion of the gain layer
- Irradiated by neutrons to equivalent fluences of 1e13, 1e14,5e14,1e15,2e15,6e15 cm-2 -> studies are made with samples as irradiated to avoid any early stage annealing surprises
- Samples were evaluated by laser and α-TCT and charge collection measurements by triggered ^{90}Sr electrons

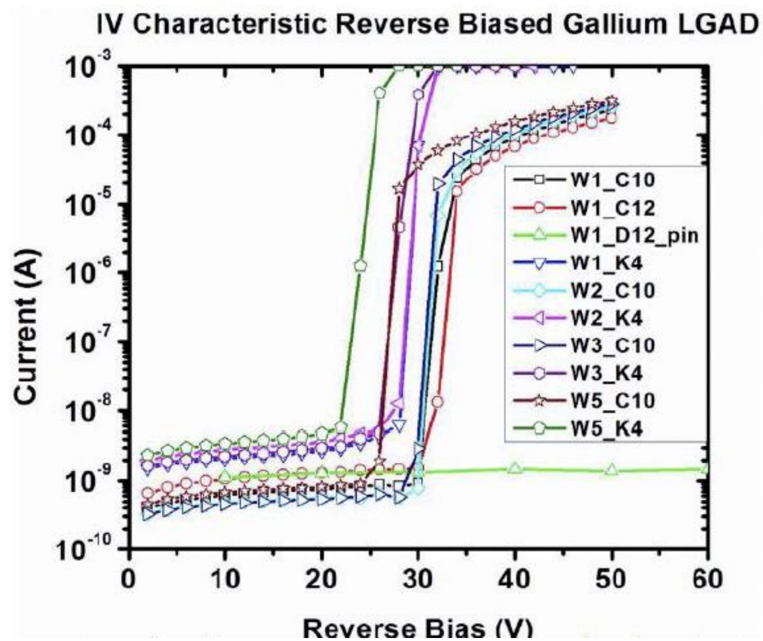


Dose4
Dose3
Dose2
Dose1
Dose0

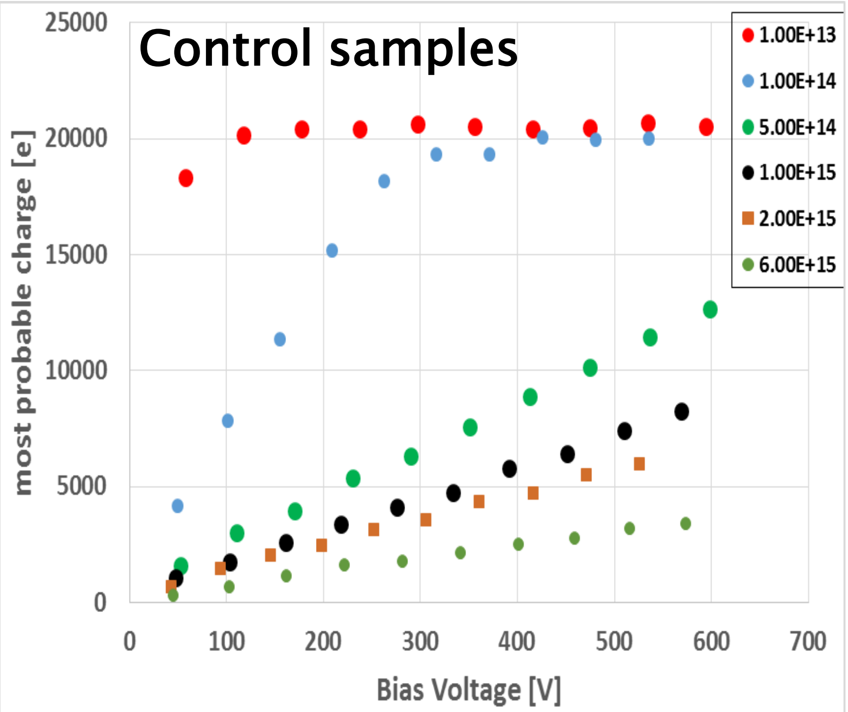
Ga implantation dose

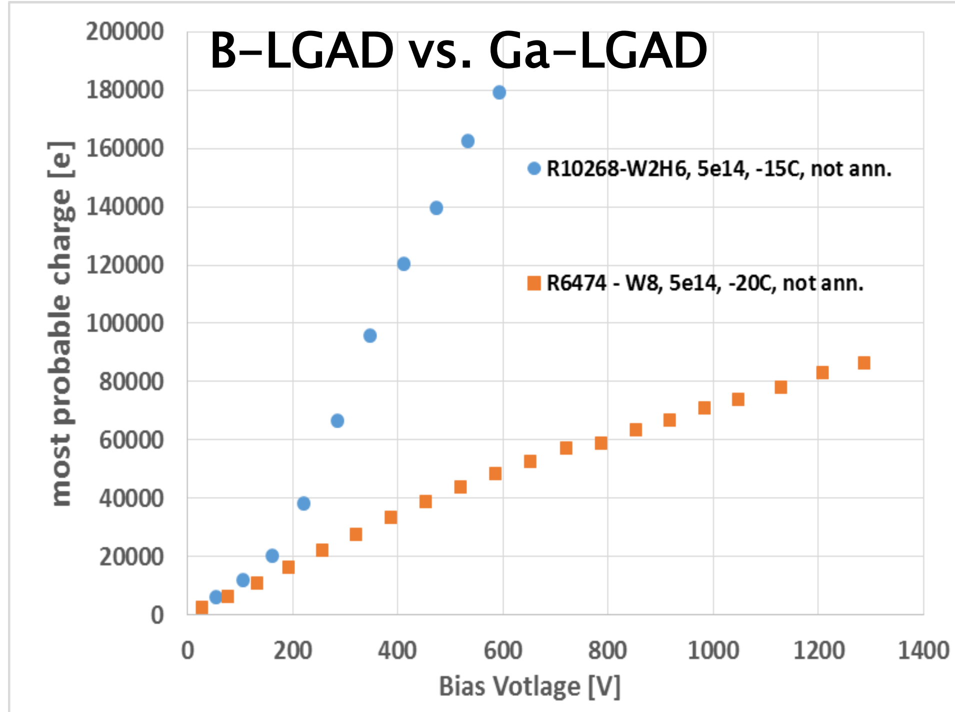
devices size 3.2x3.2 mm²
fully metallized at the back
opening for TCT at the front





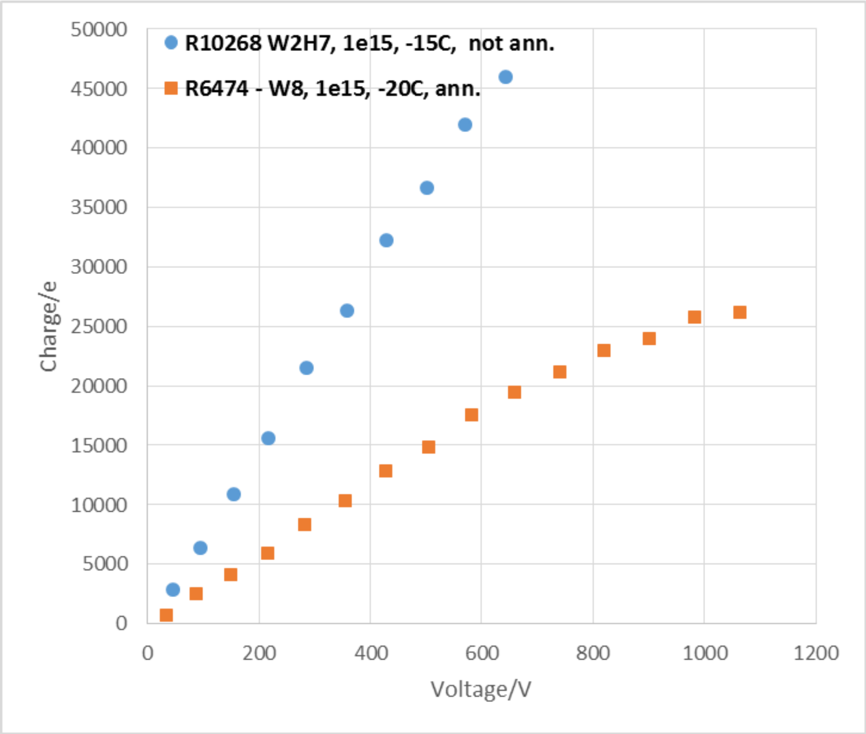
Charge collection of irradiated Ga-LGAD

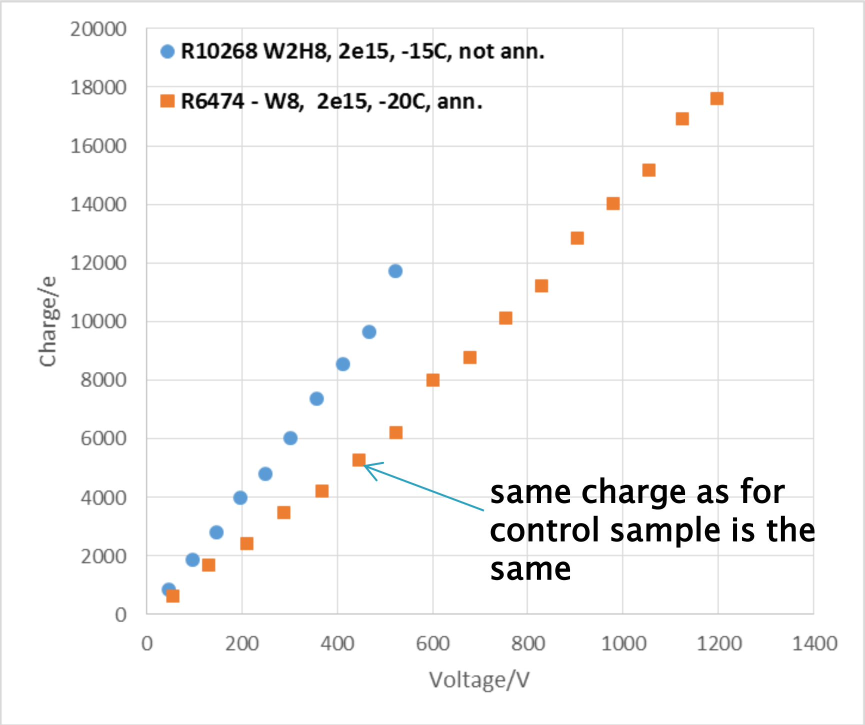




- Significant increase of charge with Ga-LGAD (Dose2 device) with respect to similar gain (estimation from "foot voltage" V_{mr}) B-LGAD after 5e14 cm^{-2}
- A factor of 3 difference in thick devices would mean much more in thin devices – easier to compensate the loss of gain due to reduced doping by bias voltage increase
- A gain of $G=Q_{LGAD}/Q_{nirr}$~9 for thick LGAD device wasn't observed before after 5e14 cm^{-2}

Charge collection of irradiated Ga-LGAD

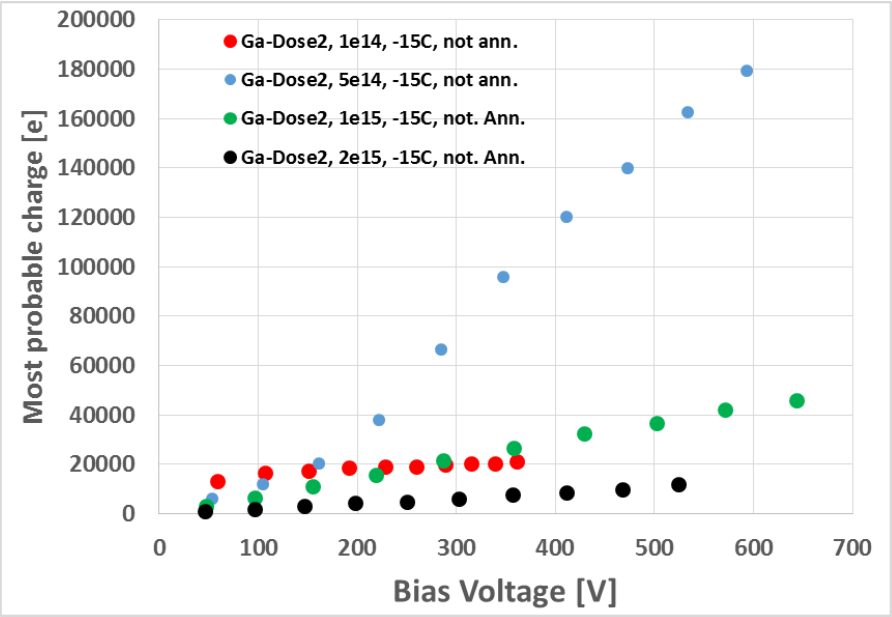


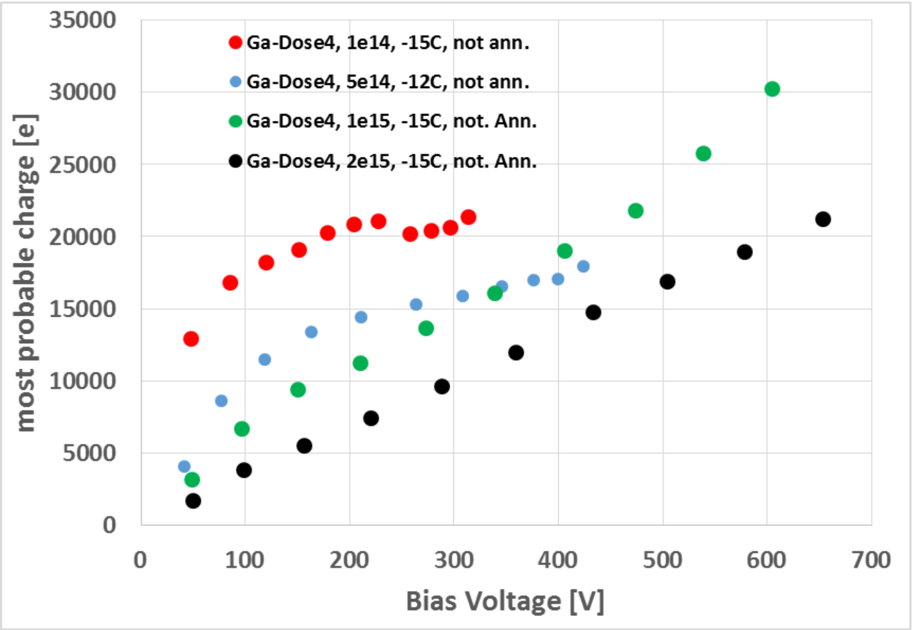


- The benefits of Ga seen also at higher fluences around 3x better at 1e15 cm^{-2} and 2x better at 2e15 cm^{-2}

Is it because Ga is more difficult to remove or the difference is due to much higher gain before irradiation?

Charge collection of irradiated Ga-LGAD





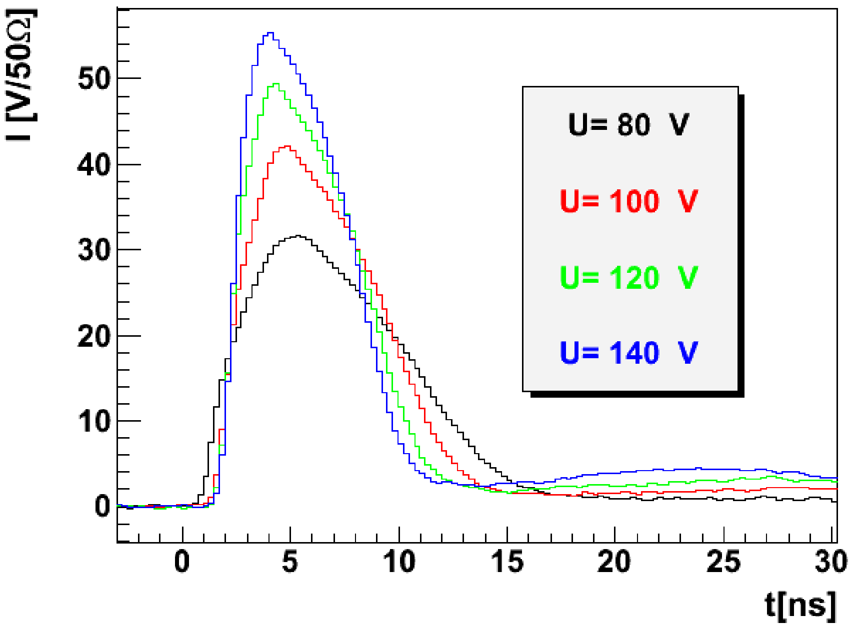
However:

- for 1e14 cm^{-2} (Dose2) device doesn't show any gain – performance of fully depleted standard detector.
- even for 5e14 cm^{-2} (Dose4) the performance is that of the fully depleted device without any gain.
- Dose 4 device performs best of all at 2e15 cm^{-2} showing significant gain.

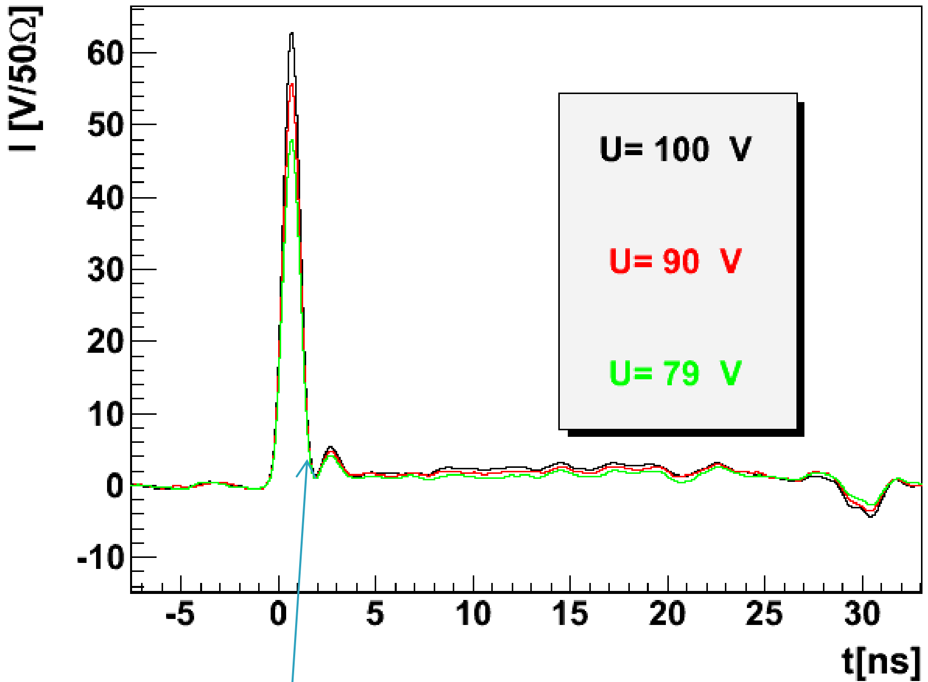
Why doesn't any additional bias voltage after full depletion result in higher gain?

Laser, α TCT (Dose2 – 10^{14} cm^{-2})

Back illumination – alpha



Front illumination 660 nm laser



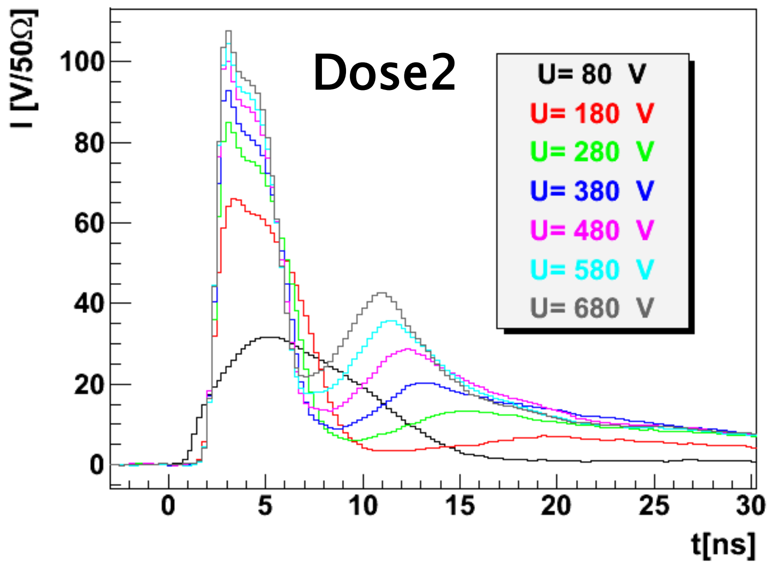
Alpha signals at low voltages indicate:

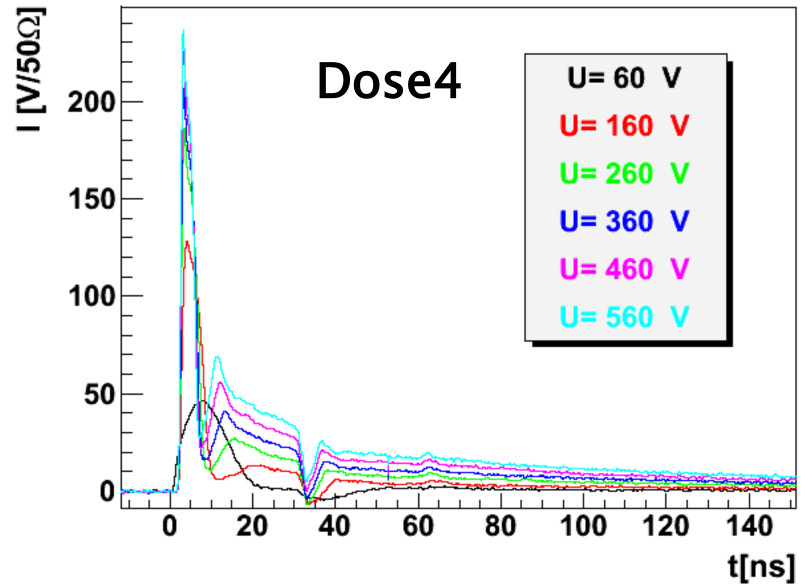
- high field region at the back
- The shape of the WFs indicates almost/close to full depletion (also seen in CCE where at 140 around 20000 e are measured for mip)

Laser signals at low voltages indicate:

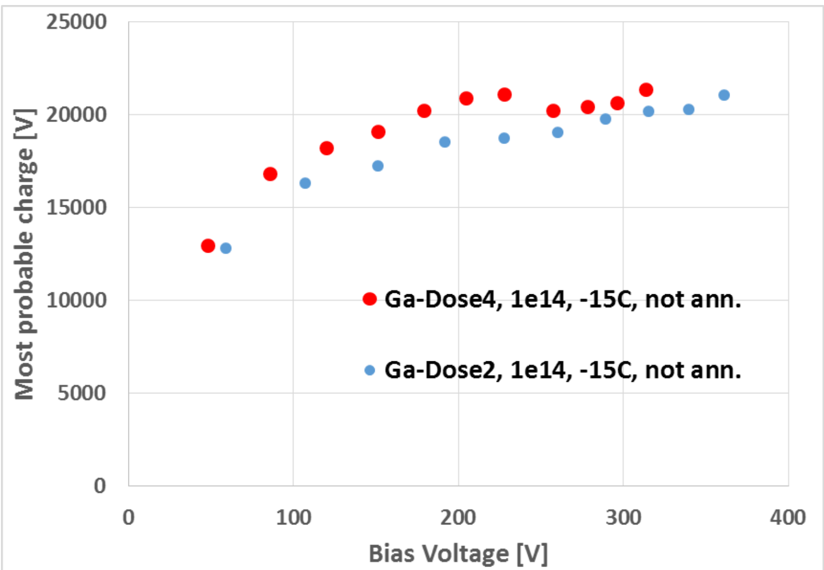
- very tiny region with field (2ns is about the sum of fall and rise time), but the amount of carriers must be very large (multiplication) to result in such large signal
- After being generated holes drift/diffuse in very low field region

Laser, α TCT (Dose 2 & Dose4 – 1e14)

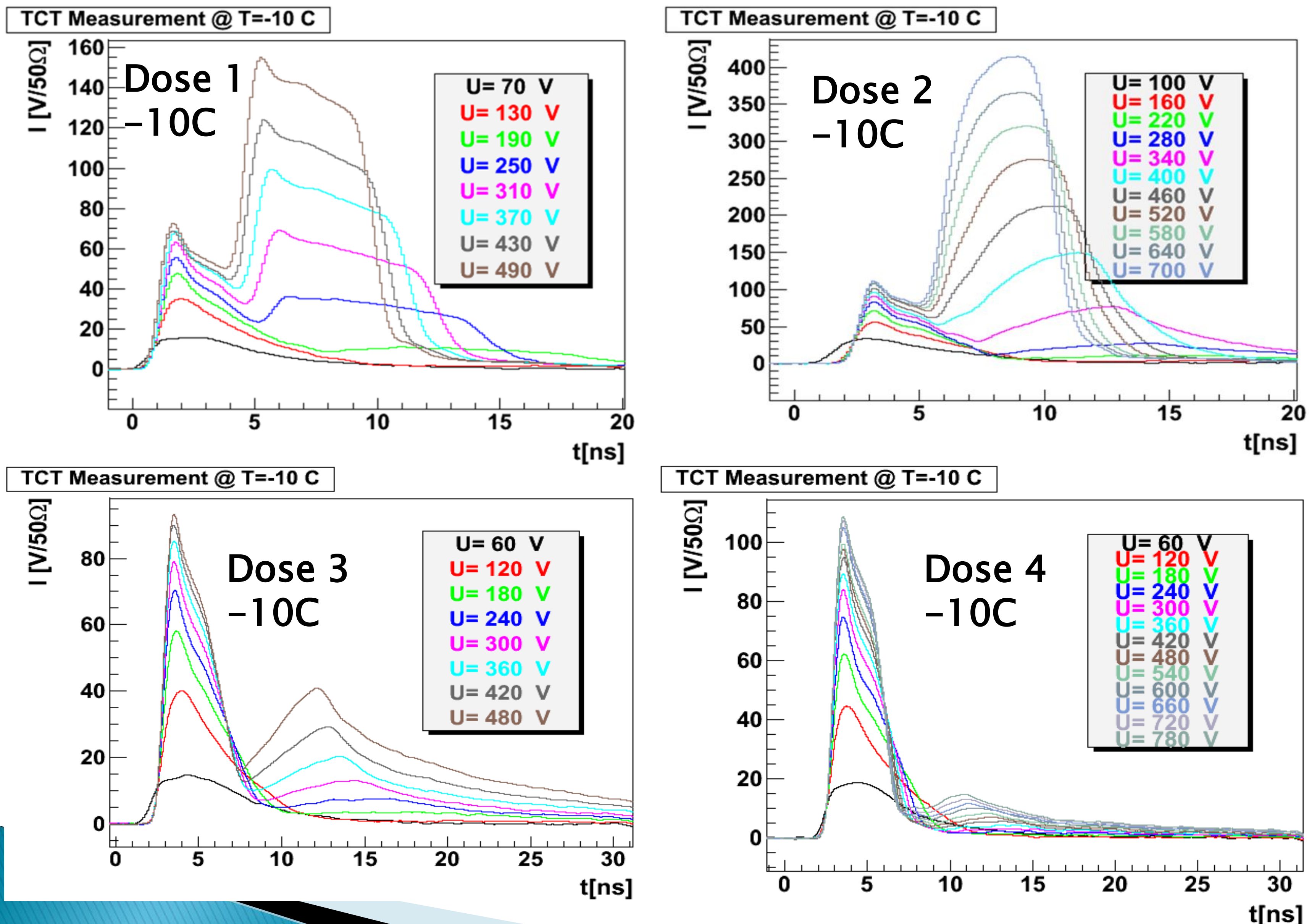




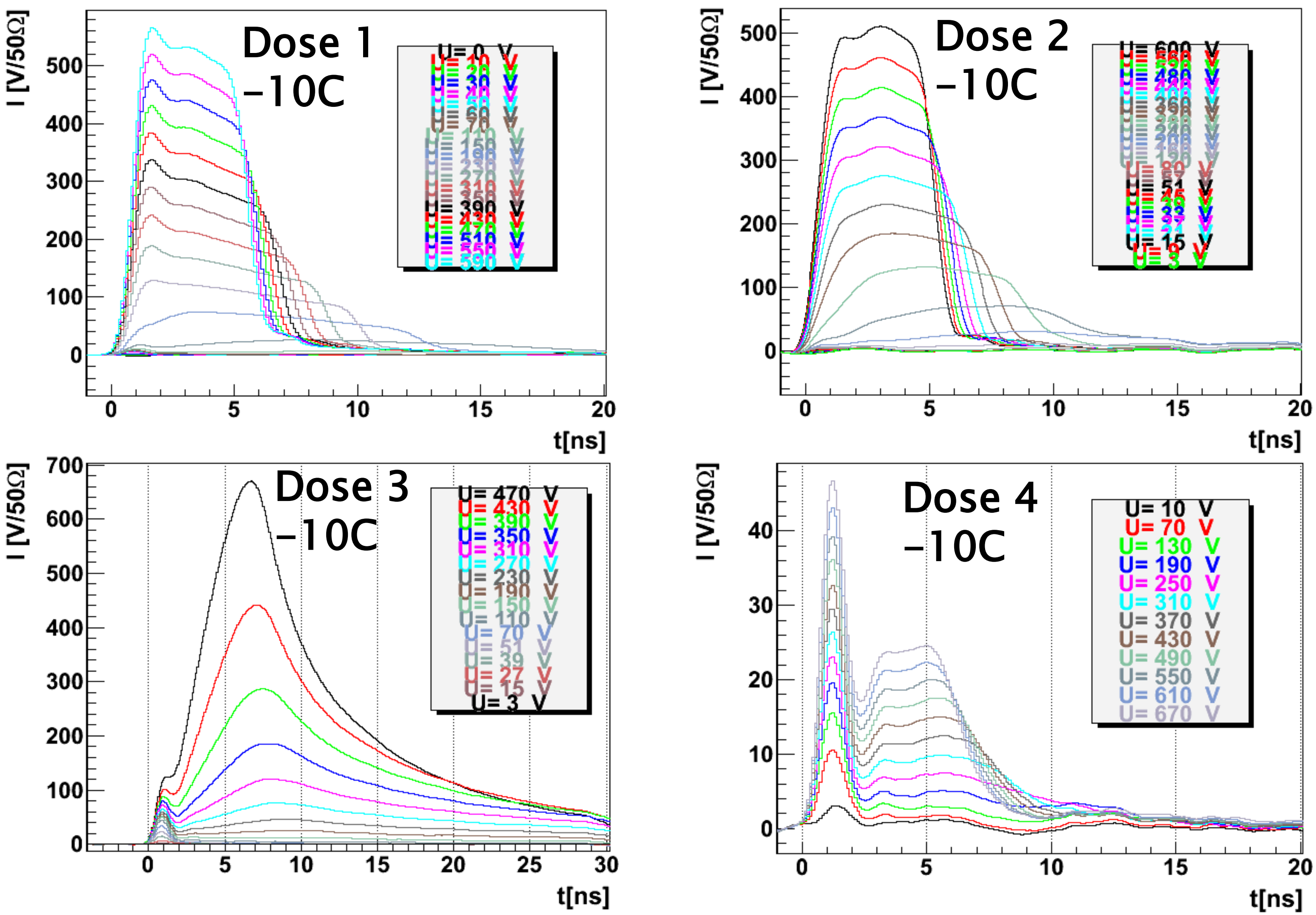
- Almost identical performance of Dose2 & Dose 4 devices – differences can only be seen after >500V
- Charge collection efficiency measured (~25 ns integration time) shows the CCE of a fully depleted sensors up to 350V – the system limits applications of larger bias voltages.
- Long tail in the signal due to: diffusion through low field region.
- TCT measurements point to large gains for very long integration times.



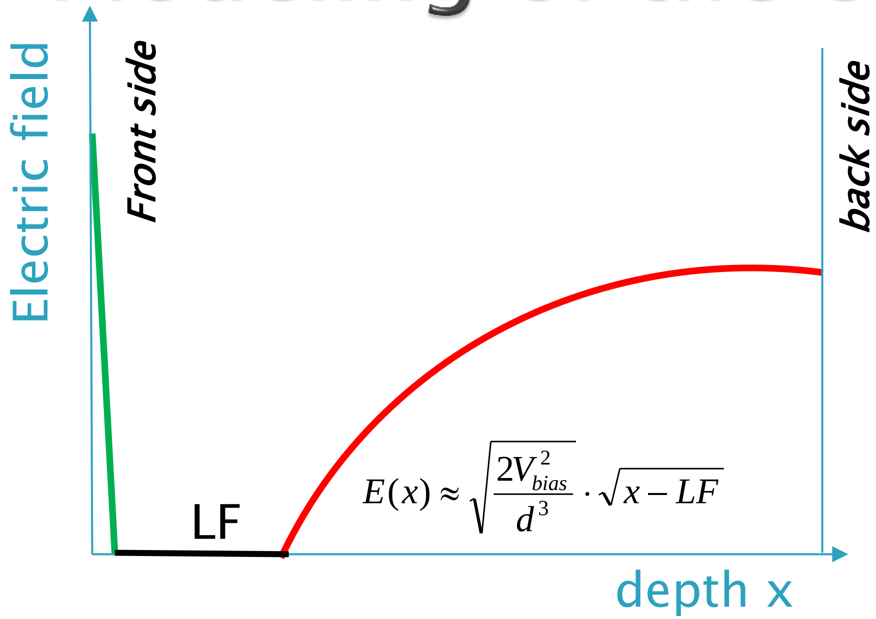
α−TCT – 5e14 cm^{-2} (from back)



Red laser-TCT – 5e14 cm^{-2} (front)



Modeling of the electric field



There are three regions in the irradiated sensor:

1.) multiplication region

2.) low field region

3.) electric field region in the bulk

Model similar to forward bias devices of RD39 (CID device):

- As soon as a gain layer depletes the hole concentration is large – high gain and from that point on the device is similar as device operated in forward direction (injection of holes)
- The hole concentration is large enough (>>trap density) to cause effectively a conductive region near the multiplication zone -> which results in very small/negligible electric field (screening)

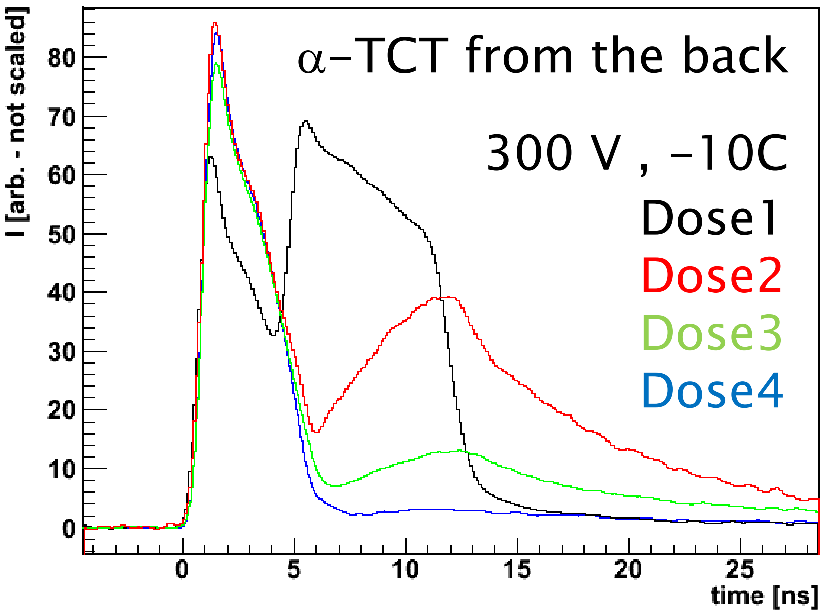
- Nuclear Instruments and Methods in Physics Research A 581 (2007) 356-360
- Nuclear Instruments and Methods in Physics Research A 583 (2007) 91-98

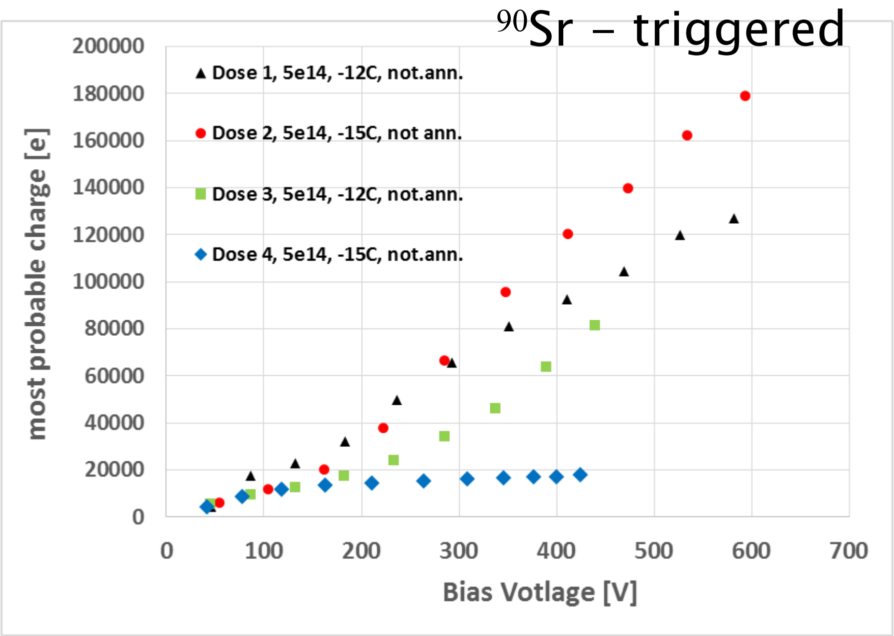
The main properties of CID operation is

- The electric field is proportional to the square root of the distance from the injection contact.
- The current is proportional to the second power of voltage.
- The increase of the concentration of trapping centres leads to the decrease of the space charge limited current.

We see first two signatures and possibly also the third in the measurements.

Modeling of the electric field – 5e14 cm^{-2}

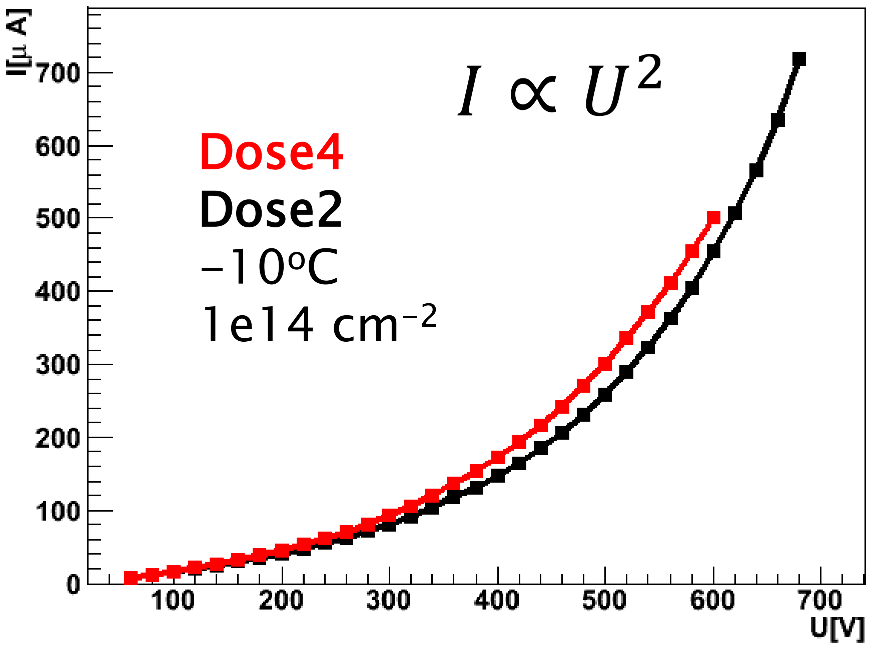


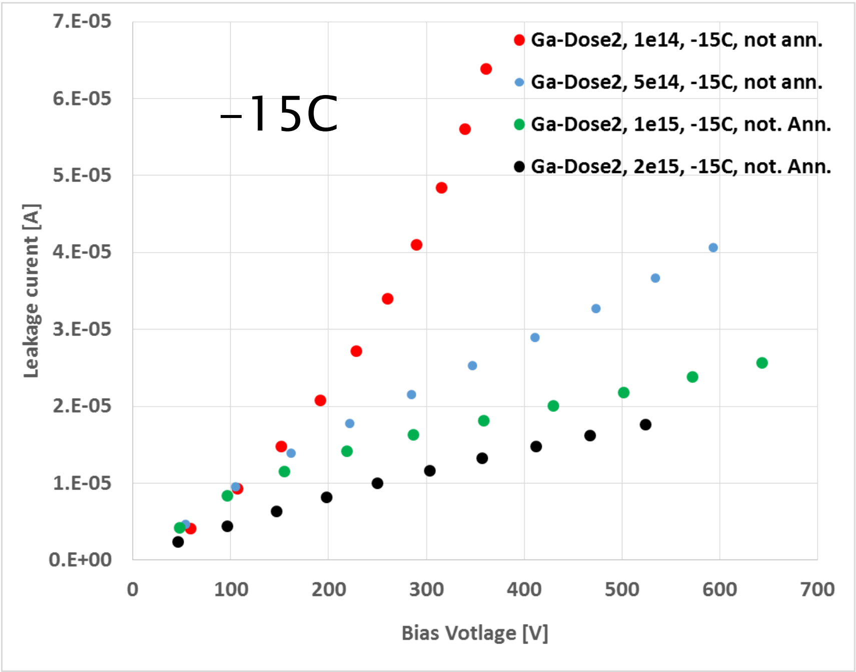


- **Dose 1** device – the gain has decreased to the level where hole supply is not enough and LF=0 ; multiplication peaks at 6ns as we are used with standard LGAD devices
- **Dose 2** device – still slightly delayed peak (LF->0), but at high voltages high gain is seen (zero field region almost not negligible)
- **Dose 3** device – mode of operation between Dose 2 and Dose 4 device
- **Dose 4** device – is mode of operation the same as for 1e14 Dose 4 device

Decrease of gain/increase of deep traps "standard LGAD performance" where LF->0

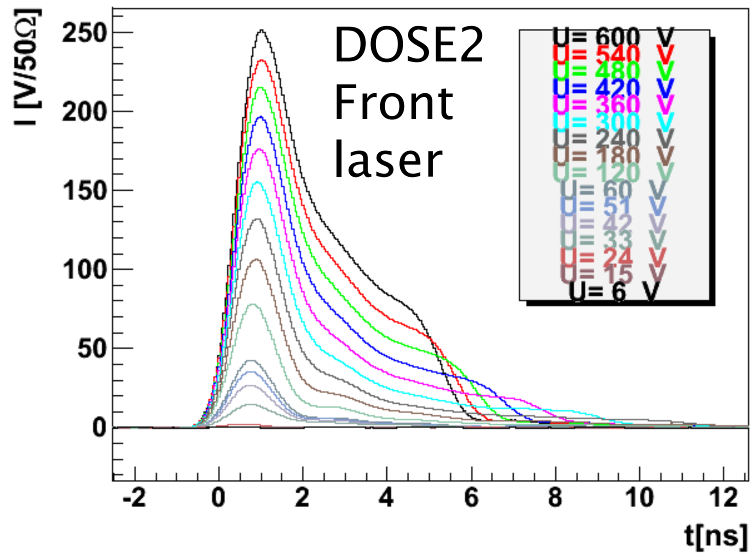
Leakage current

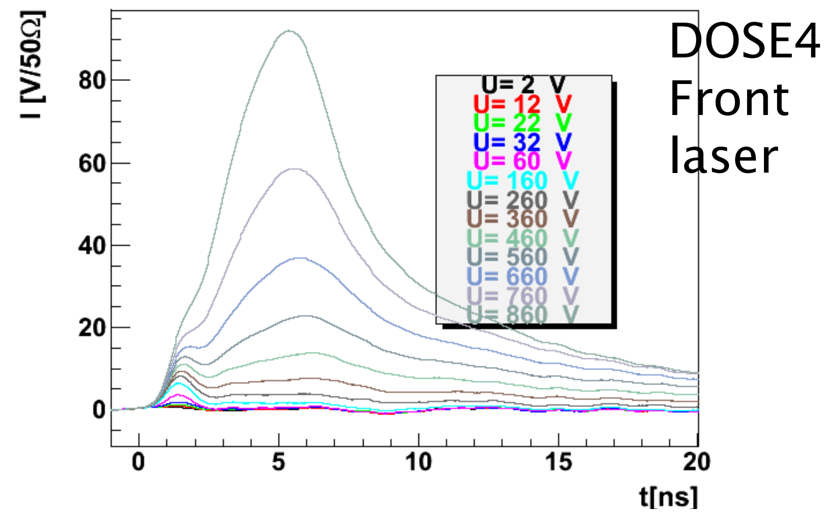


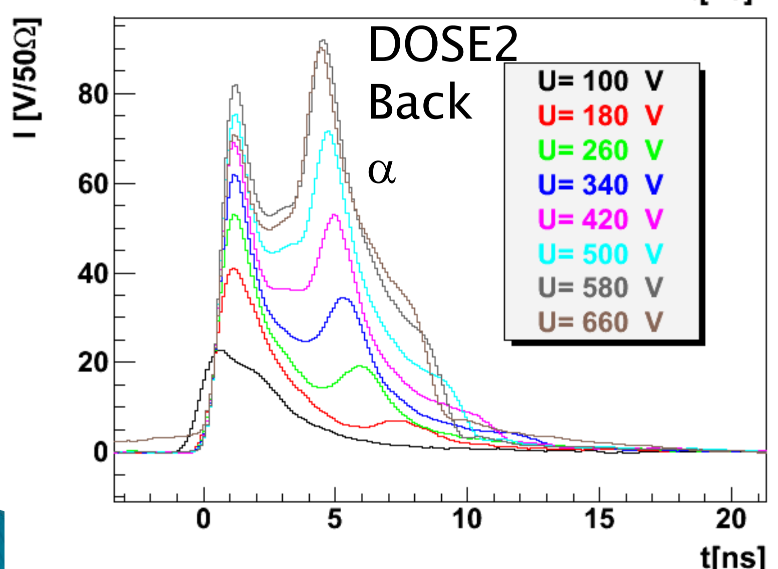


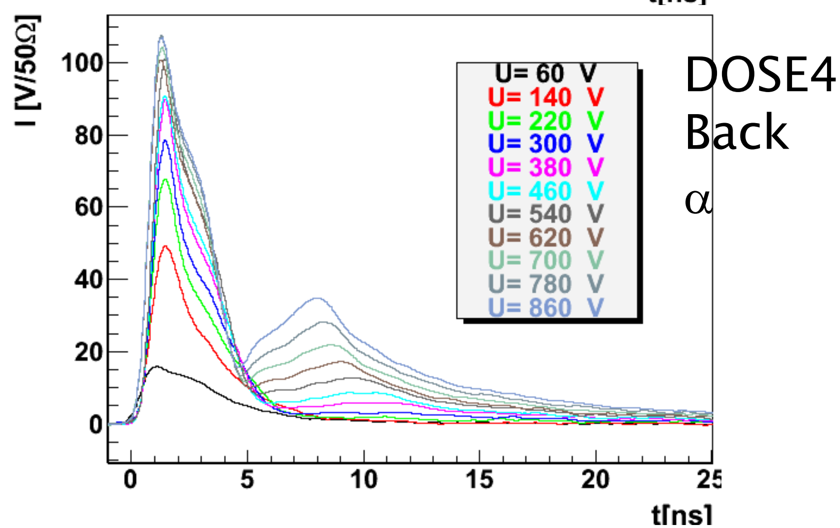
- Very high current and exhibits, an indication of CID device (Space charge limited current):
  - decrease of leakage with fluence (not this is also due to decreasing gain)
  - Quadratic dependence on voltage at lower fluences where LF≠0

Laser, α TCT (Dose 2 & Dose4 – 1e15)



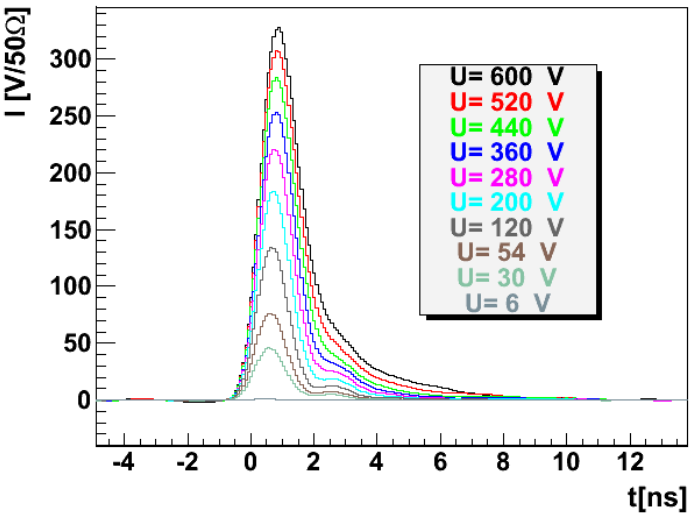




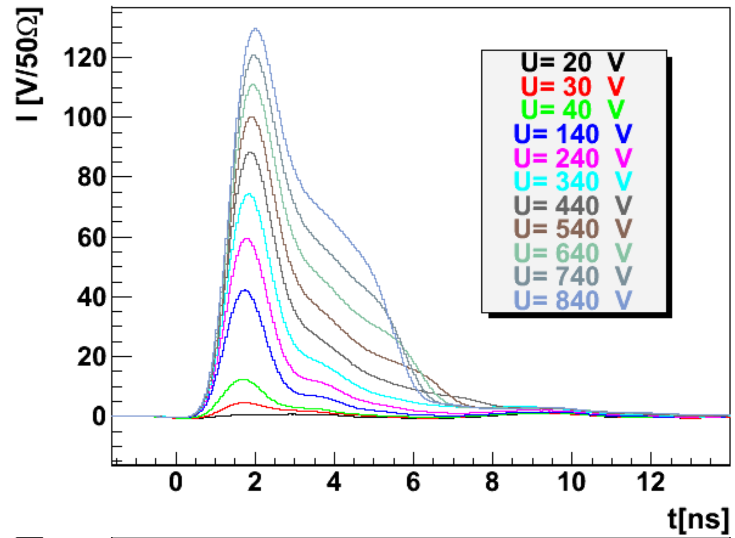


Laser, α TCT (Dose 2 & Dose4 – 2e15)

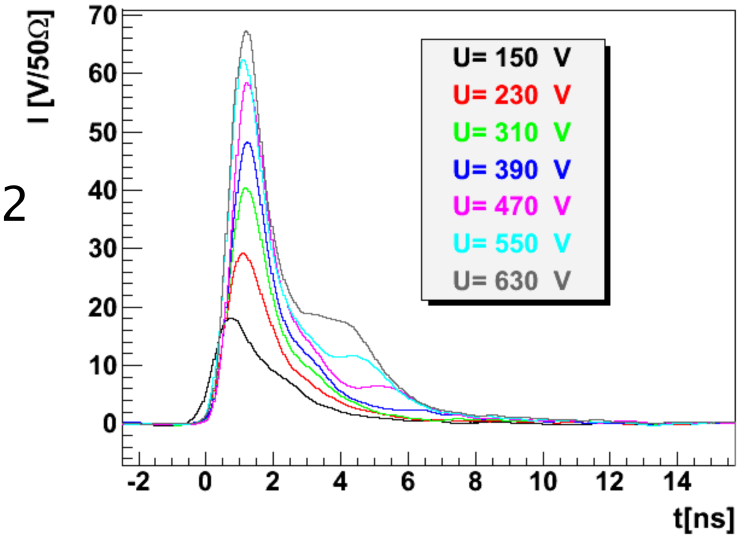
DOSE2
Front
laser



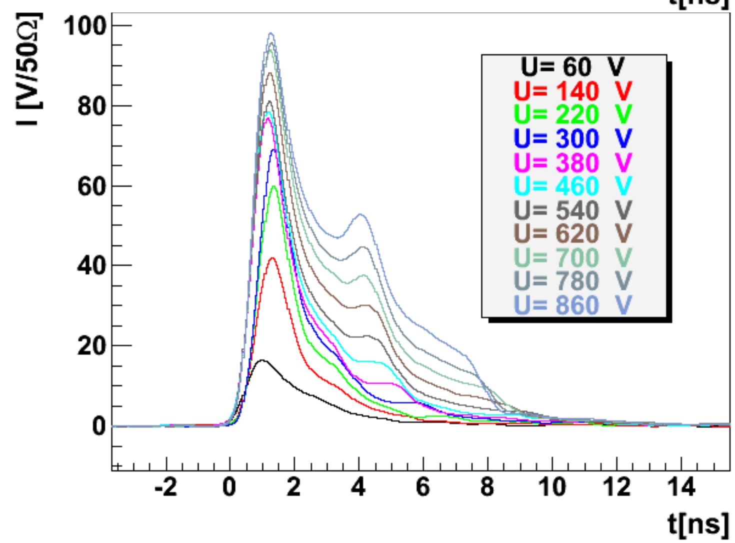
DOSE4
Front
laser



DOSE2
Back
α

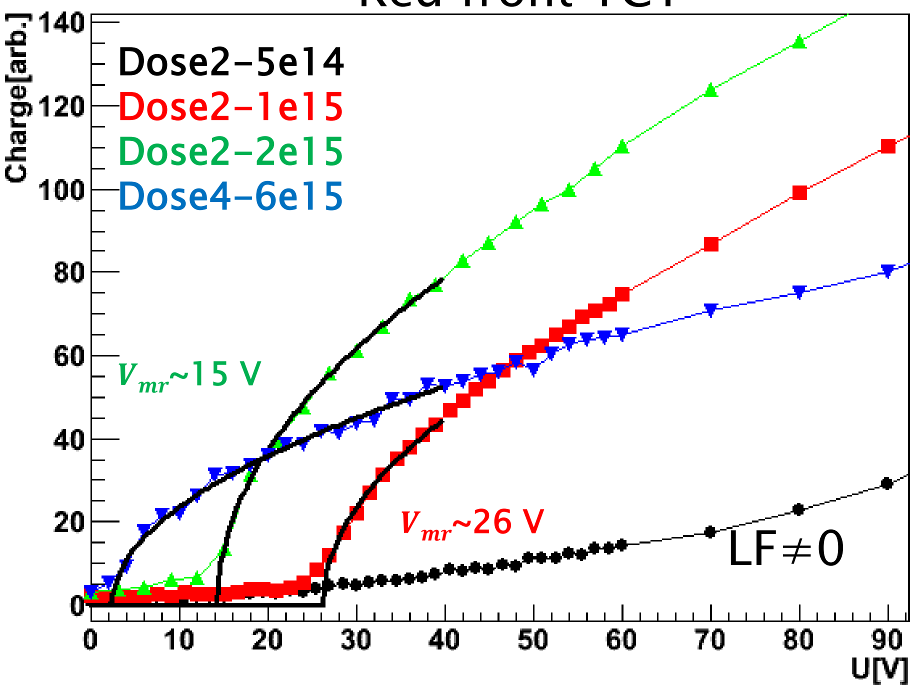


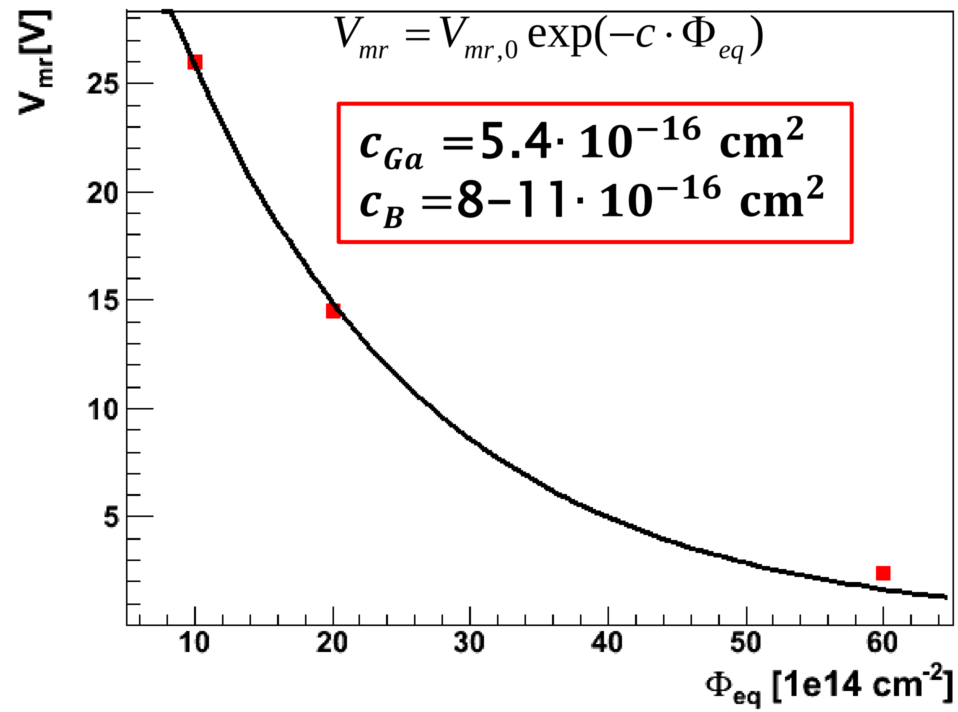
DOSE4
Back
α



Is Ga better than B?

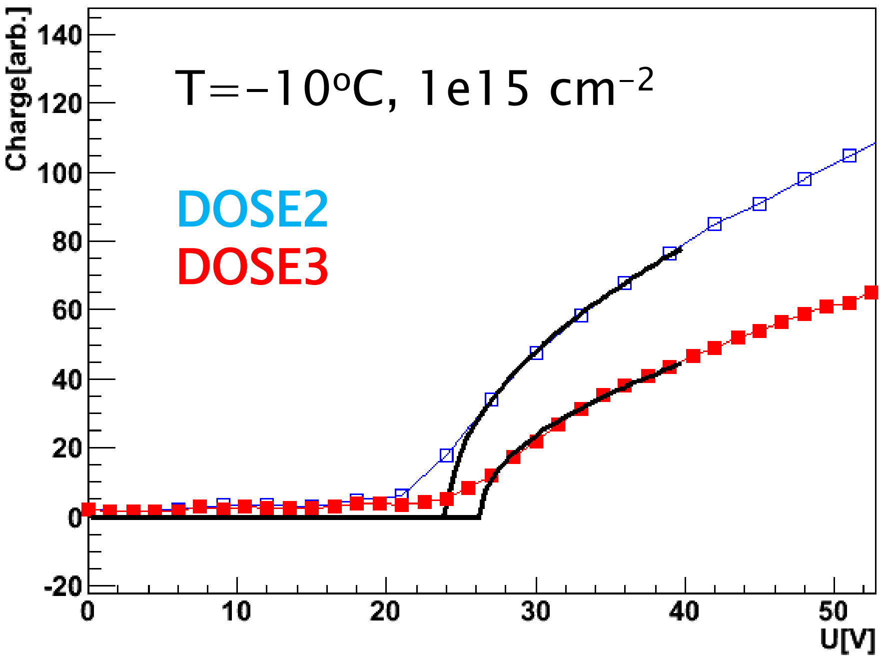
- It is difficult to compare the measurements as we don't have devices with the same gain to start with
- The comparison can be made after the devices switches back to "standard LGAD mode" – the foot can be used for evaluation of gain layer depletion

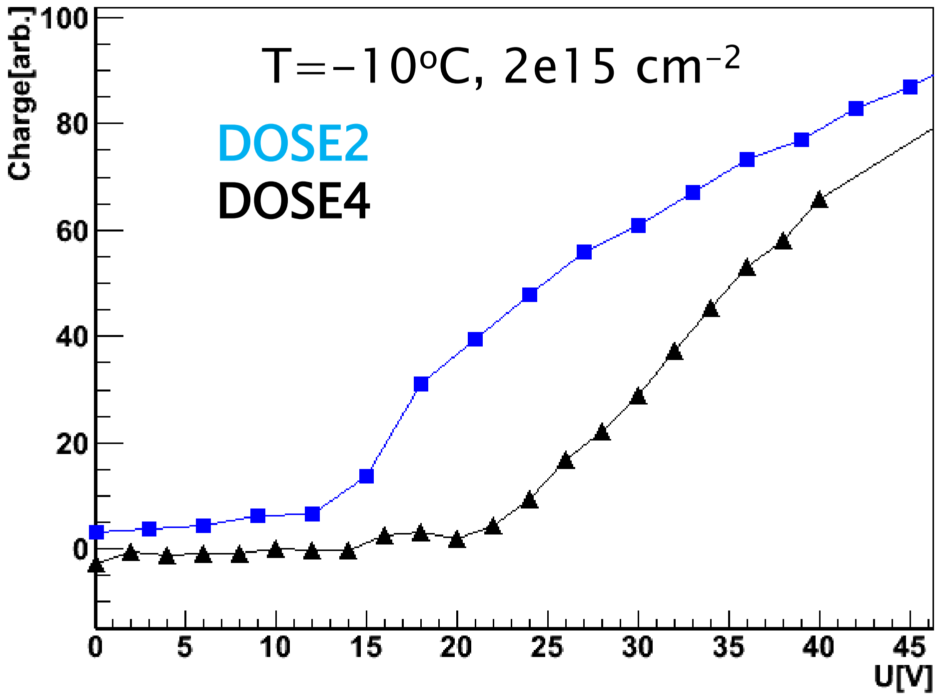




Removal constant c~5e-16 cm^2 **(around factor 1.5-2 smaller than for B)** – this is also in agreement with m.i.p. charge measurements (less decrease for 1e15 cm^{-2})

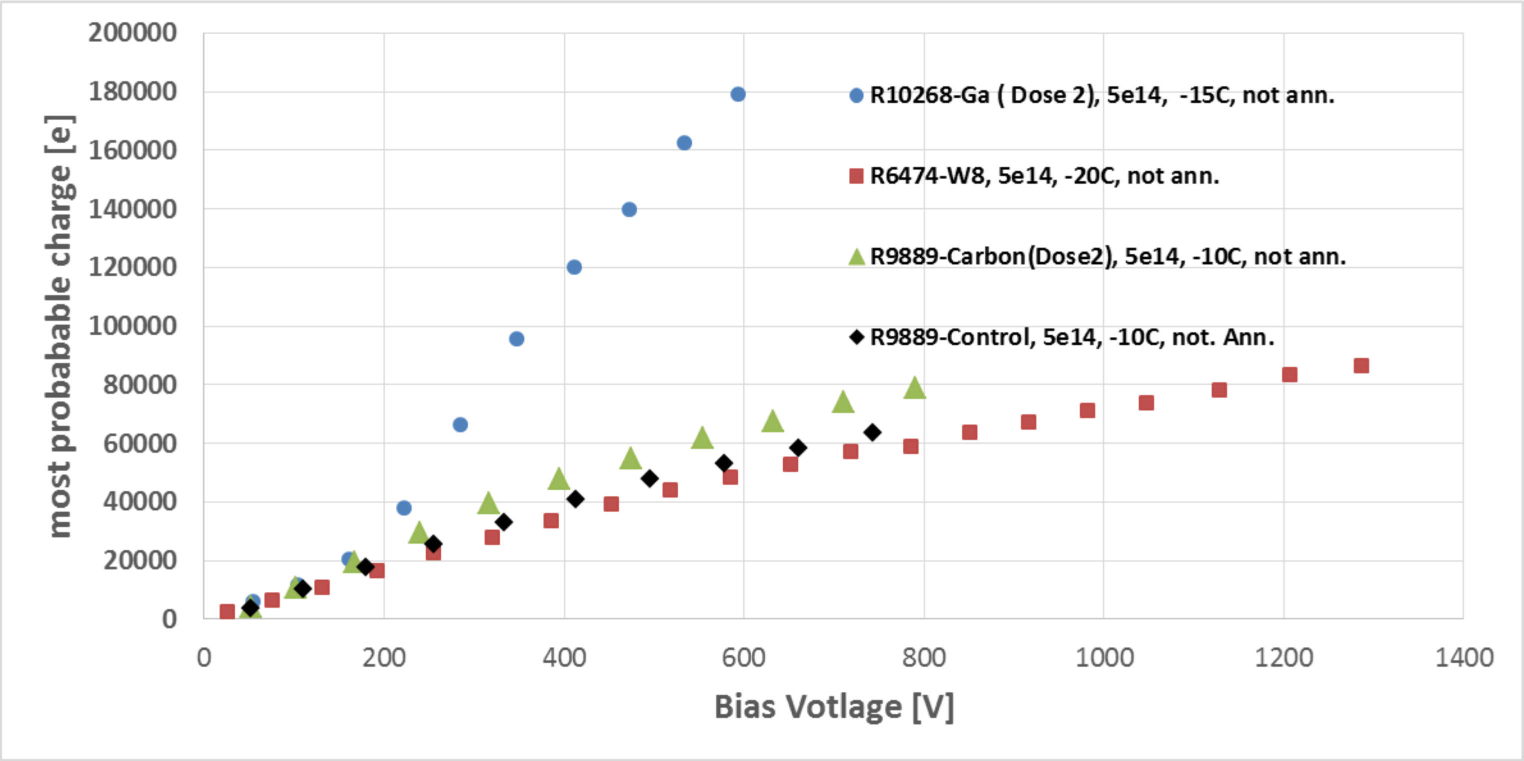
Ga dose and V_{mr}





Difference in Ga dose persists in approximately the same ration as before irradiation also at high fluences

B-LGAD/C spray- Measurements



- Annealing hasn't been done – may play a role.
- Improvement is small ~20% – question is how much C is enough . We just started the program – more data will follow soon.
- Improvement should be larger for 23 GeV protons.

Conclusions

- Ga-LGAD produced by CNM with 4 different gains:
  - gain was too high in all and leads to early breakdown before irradiation – $V_{mr}>30\text{-}35$ V
  - after irradiations the devices work
- Larger charge collection than in the boron doped devices was observed:
  - Larger initial gain – very high concentration of Ga
  - Smaller removal constant – **about twice smaller than in B doped devices**
- A model similar to CID devices (RD39) was proposed to quantitatively describe the results in the whole fluence range
  - at lower fluences the devices operates as almost fully depleted detector with no gain
  - after the gain drops it operates as a standard LGAD.

⇓

Production of thin Ga-LGADs as RD50 project ….